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Fighting coal — Effectiveness of coal-replacement programs for residential heating in China: Empirical findings from a household survey

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ABSTRACT

Household fuel substitution has been a crucial step for controlling air pollution in China, but the performance evaluation of household fuel substitution policies is overlooked. This study capitalized on the opportunity to use data collected during the household coal-replacement program in North China to evaluate the effect of a mandatory policy on fuel substitution at the micro-level. The results indicate that there is a significant effect of the coal-replacement program on fuel substitution, as we expected. The coal-to-electricity policy is effective in achieving the goal of a clean winter but not a warm winter due to the decline of delivered energy, while the high-quality coal replacement policy results in better performance in delivered energy but no improvement in indoor air quality. It is recommended to prioritize supporting measures on both the supply and demand sides before implementation, along with undertaking differential measures during the implementation phase to better address energy inequality.

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Introduction

Many developing countries do not recognize the significant role that residential cooking and space heating with solid fuels plays in increasing air pollution (Cheng et al., 2017; Liu et al., 2016; Zhi et al., 2017). Due to the lack of access to affordable and clean alternatives, >3 billion people rely on biomass and coal for cooking and heating, leading to the most important direct health risk from this practice — household indoor air pollution (WHO, 2014). In 2016, household air pollution contributed to 3.8 million premature deaths (WHO, 2018). Inefficient use of solid fuels also contributes to ambient air pollution, which poses not only a health threat, but also a significant contribution to global warming (WHO, 2018). As one of the UN Sustainable Development Goals (SDGs), ensuring access to affordable, reliable, sustainable and modern energy is a crucial step to achieving almost all the other goals; from its role in the eradication of poverty through improvements in health, education and gender inequality and combatting environmental damage and climate change (Fuso Nerini et al., 2018; UN, 2016). Expanding access to clean and affordable energy sources is a rallying point of these issues, and residential fuel switching or fuel substitution is a viable strategy to accomplish those goals.

In the past few years, heavy smog has blanketed various regions in China, where regional air pollution characterized by particulate matter (PM_{10} and $PM_{2.5}$) has become increasingly prominent. This situation triggered the Chinese government to take steps to fight against air pollution. Massive household fuel substitution programs were launched, which provides us with a good opportunity to study the effect of mandatory household fuel substitution. In 2013, the *Air Pollution Prevention and Control Action Plan* was issued by the State Council in China. Coal control is a critical part of the action plan, and measures like replacing coal with natural gas or electricity and the establishment of clean coal distribution centers in the residential sector are included. The promulgation of the plan is a key milestone in China's war on pollution, and it introduces mandatory household fuel substitution in China. In the following years, a series of policies about household fuel substitution were issued, as listed in Table 1.

In light of these policies, scattered coal[1] replacement programs — especially programs implemented during the heating seasons of the residential sector — are becoming pivotal measures for reducing air pollution in China. It is estimated that about 200 million tons of scattered coal were used for heating in rural China in 2015 (NRDC, 2017). Emission reduction from the residential sector through the replacement of solid fuels with clean energy could improve air quality more than from other sectors in the Beijing-Tianjin-Hebei (BTH) region of China (Liu et al., 2016). Since the measures are mainly aimed at the heating

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[1] Scattered coal refers to decentralized burning of coal of low combustion efficiency that is highly polluting and it is mainly used in the residential sector (e.g., space heating and cooking) and in some industrial boilers.

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Table 1
Policy review of the household fuel substitution of China in recent years.

Policy	Year	Coverage	Description
Air Pollution Prevention and Control Action Plan	2013	Nationwide	Replacement of coal with natural gas or electricity and establishment of the clean coal distribution center
Strengthening Measures for Jing-Jin-Ji Air Pollution Prevention (2016–2017)	2016	Beijing, Tianjin, Baoding, Langfang, Tangshan, Cangzhou	Driving the coal-to-gas and coal-to-electricity transition and eliminating coal use by 2017 in plain area; defining the area where coal is forbidden
Work Plan for the Control of Greenhouse Gas Emissions during the 13th Five-Year Period	2016	Nationwide	Accelerating the replacement of coal for residential heating
Work Plan for Air Pollution Prevention and Control in Jing-Jin-Ji and Surrounding Areas in 2017	2017	Air Pollution Transmission Channel City of Beijing-Tianjin-Hebei ("2 + 26" cities)	Promoting clean heating comprehensively; Each city meets the target of 50,000–100,000 households for coal-to-gas and coal-to-electricity switching; new residential buildings can only use electricity, natural gas, geothermal and air-source heat pump for heating, and are not allowed to build coal-fired boilers.
Notice of the National Energy Administration (NEA) on the Implementation of the Central Financial Support for the Winter Clean Heating in Northern Region	2017	Priority: "2 + 26" cities	Support pilot cities to promote clean heating instead of scattered coal combustion for heating; the standard funding amount is determined by the city scale (municipality: 1 billion yuan/year; provincial capital city: 700 million yuan/year; prefecture-level cities: 500 million yuan/year)
Action Plan of Comprehensive Management of Air Pollution for Jing-Jin-Ji and Surrounding Areas in the Autumn and Winter of 2017–2018	2017	"2 + 26" cities	Accelerating the comprehensive treatment of scattered coal pollution; "2 + 26" cities meet the target of 3 million households for coal-to-gas and coal-to-electricity switching by 2017; promoting the use of clean coal for areas that cannot implement the coal substitution policies
Clean Warm Winter Planning in the Northern Region (2017–2021)	2017	14 provinces including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Shaanxi, Gansu, Ningxia, Xinjiang, and Qinghai, and parts of Henan province (covering "2 + 26" cities")	By 2019, the clean heating rate in the northern region reaches 50%, replacing 74 million tons of scattered coal (including low-efficiency small boiler coal). By 2021, the clean heating rate in the northern region reaches 70%, replacing 150 million tons of scattered coal.
Notice on Expanding the Central Financial Support for the Winter Clean Heating Pilot City in the Northern Region	2018	"2 + 26" cities, Zhangjiakou, cities of the Fenhe and Weihe plain	"2 + 26" cities and Zhangjiakou receive the same funding as that in 2017; other cities are supported by 300 million yuan/year.
Three-year action plan for Winning the Blue-Sky Defense War	2018	Beijing, Tianjin, Hebei and surrounding areas	Promoting clean heating effectively; completing the scattered coal replacement by 2020, promoting the use of clean coal, and strengthening the supervision of coal quality for areas with no conditions for coal replacement; the energy efficiency of the gas boiler should not be lower than the level 2 level.
Action Plan of Comprehensive Management of Air Pollution for Jing-Jin-Ji and Surrounding Areas in the Autumn and Winter of 2018–2019	2018	"2 + 26" cities	Promoting clean heating effectively; planning for warm winter and clean heating overall; determining the number of households that can covert to "coal-to-gas" and "coal-to-electricity" reasonably; no demolition of the original heating facilities for areas without enough gas and electricity; severely cracking down on the sale of inferior coal

season, a clean, warm winter should be two parallel aims of launching the scattered coal replacement programs.

Specifically, *coal-to-gas* and *coal-to-electricity* for household heating are the two major forms of scattered coal replacement programs, while *high-quality coal replacement* is an additional strategy for areas unable to provide clean energy alternatives. The focus areas of the coal replacement are "2 + 26" cities, namely the air pollution transmission channel cities of Beijing-Tianjin-Hebei. Regulated by these policies, residents in these areas are not allowed to burn scattered coal in winter for heating, and they can only use natural gas or electricity with financial subsidies for three years. The national and local governments also subsidize the purchase of electric heating or gas heating devices. For villages unable to switch coal to clean energy, they can only buy coal of higher quality, and inferior coal is prohibited from being sold.

The unintended effects of these policies are becoming a key area of concern in China. For example, the shortage of gas in Hebei province leads to a reduction in delivered energy and cold conditions for residents. It is estimated that in the winter of 2017, the natural gas shortage was up to 4.8 billion and 11.3 billion cubic meters in northern China and the whole nation, respectively (Li, 2018). At the same time, the insufficient gas supply elevated the gas price, putting the heating cost beyond residents' reach even though financial subsidies were provided. Given these previous experiences and continued supply constraints, it is unlikely that the residents will be able to use modern fuels in three years when the subsidy is no longer in effect. In addition, the slow pace of the infrastructure development hampers adequate heating in some rural areas. These unintended effects and remaining challenges emphasize the need to evaluate whether these policies have met their initial goals. Although debate on the issue and research about the health and environmental effect of these policies is extensive, little attention has been devoted to quantifying the effect on household fuel consumption due to the data availability, which affects residents' welfare directly.

The aim of this study was to investigate the effect of household scattered coal-replacement programs on household fuel consumption at the micro level and answer the question of whether the dual goals of clean air and a warm winter were achieved. Benefitting from data collected in a novel household survey for Beijing, we analyzed the fuel substitution effect of coal-replacement programs. Apart from the average treatment effect of the coal-replacement programs, the heterogeneous effect treatment was also analyzed as research on the heterogeneous effect can help inform policy-makers under which conditions policies are effective or ineffective, and help inform them of ways to design and deploy policies. Finally, a structured questionnaire of heating devices allowed us to evaluate the delivered energy; namely, the energy delivered to residents before and after the treatment. This paper also discusses the difference of the mandatory fuel substitution and energy ladder impelled by economic growth.

This paper proceeds as follows. Literature review reviews relevant research related to fuel substitution programs in other countries and the coal-replacement program in China. Methodology and data briefly introduces the household survey and the research method. Results describe the results of the empirical study of the policy effect and the variation of delivered energy and indoor air pollution. Discussion and conclusion discusses the mandatory policy of fuel substitution and spontaneous substitution driven by income growth, and provides conclusions on the research.

Literature review

This section reviews the effect of household fuel substitution in the world and the main research domains of the residential coal replacement policy in China.

Considerable research has studied the energy switching intervention. Two popular measures for energy switching programs are fuel bans and clean energy substitution by providing improved appliances or stoves. Bans on traditional solid fuels are known to be effective in alleviating air pollution (Kerimray et al., 2017). In Dublin, Ireland, the implementation of coal bans has been found to decrease respiratory and cardiovascular deaths and reduce pollutant emissions significantly (Clancy, Goodman, Sinclair, & Dockery, 2002). For more information on measures of fuel bans in European countries, please see North South Ministerial Council (NSMC, 2016). As for the clean energy alternative not associated with new appliances, Budya and Yasir Arofat (Budya & Yasir Arofat, 2011) analyzed the large-scale energy switching program in Indonesia and found that the conversion of kerosene to liquid petroleum gas (LPG) was successful after the kerosene subsidy was removed. A clean energy subsidy is the most effective policy to support fuel-switching in India's rural communities (Pachauri, Rao, & Cameron, 2018). Still, it is important to note that the higher costs for modern fuels may hinder energy upgrades. In Mongolia, for example, the electricity expense is still twice that of coal, even at the valley price (WB, 2009).

Much research has attempted to analyze the implementation of stove or appliance substitution, and many scholars have verified the role of improved stove or appliance programs in mitigating air pollution and climate change, as well as the positive effects on health outcomes ((Bailey, 2017); Grieshop, Marshall, & Kandlikar, 2011; Ochieng, Vardoulakis, & Tonne, 2017). Adkins, Tyler, Wang, Siriri, and Modi (2010) compared the fuel consumption of manufactured stoves to three-stone fires and suggested that the use of improved cookstove technology greatly increases residents' overall welfare. Scott and Scarrott (Scott & Scarrott, 2011) examined the effect of a cleaner heating technologies program in New Zealand and estimated the significant decline of PM emissions and concentrations. In developing countries, cooking stove replacement is common. Even though co-benefits of the stove replacement program are great, the low adoption rate is a barrier (Ruiz-Mercado, Masera, Zamora, & Smith, 2011). El Tayeb Muneer and Mukhtar Mohamed (El Tayeb Muneer & Mukhtar Mohamed, 2003) and Jan (Jan, 2012) used regression analysis to examine the adoption rate and the factors affecting the adoption rate of improved cookstoves in Sudan and Pakistan, separately. Agurto Adrianzén (Agurto Adrianzén, 2011) found that even if 69% of households were provided with free improved cookstoves, the adoption rate was only 45% in Peru. For similar research, refer to Malla and Timilsina (Malla & Timilsina, 2014). By using difference-in-differences estimation techniques, Jagger, Das, Handa, Nylander-French, and Yeatts (2019) examined the relationship between the adoption of the improved cooking stoves and household fuel expense, health and time spent cooking in Rwanda. Murphy (Murphy, 2001) examined the effect of the conventional grid expansion, renewable electricity, and improved cookstoves in East Africa, and the results showed that energy transition is an incremental process instead of a leaping process.

In developed countries, energy transition in heating and lighting are more of a focus. Michelsen and Madlener (Michelsen & Madlener, 2016) investigated the barriers in switching from a fossil fuel heating system to a renewable heating system and found that the willingness to abandon old habits and the perceptions of the new heating system are two important determinants. In Spain, a boiler renovation plan was implemented, but the program witnessed a low reduction in $PM_{2.5}$ emission due to unchanged biomass consumption (NSMC, 2016). Frondel and Lohmann (Frondel & Lohmann, 2011) explored the reasons for the low adoption of energy-saving light bulbs relative to conventional light bulbs. However, although these kinds of studies belong to energy efficiency programs, they are more about energy saving than about energy transition.

As the scattered coal replacement policies are developed and refined in China, an increasing number of scholars have started to conduct research on residential coal substitution in China. Three specialized reports have done substantial and comprehensive work on the topic, with different emphases. National Resources Defense Council (NRDC) conducted research and analysis not only on residential coal control but also on industrial boilers (NRDC, 2017; NRDC, 2018). Of these reports, NRDC reports focuses more on the macroscopic perspective. The third one is Li, Liu, Yang, Hu, and Tan (2017), which focuses on the policy progress and challenges in the BTH regions using policy review and a household survey. It is more of a descriptive analysis than a deeper quantitative analysis.

In addition to ad-hoc reports about the policy and programs, many scholars have carried out research into China's coal switching policy. The focus on the Cost and Benefit Analysis (CBA) and the effect on the emission reduction are the two most common domains of focus. Even before the policy was implemented, the environmental–economic–technical rationality of coal-to-gas in residential cooking and heating was reviewed by Mao, Guo, Chang, and Peng (2005). The results demonstrated the feasibility of substituting natural gas for coal but emphasized the necessity of a natural gas penetration incentive policy.

For CBA research, economic, health, and environmental effects — especially reduction effects on greenhouse gas emission and air pollutant emission — were studied. For example, Zhang, Jin, Dai, Xie, and Zhang (Zhang, Jin, Dai, Xie, & Zhang, 2019) proposed an integrated assessment model to explore the health effects and the economic costs of cleaner residential heating in the BTH region. Based on the life cycle assessment, Zhang and Yang (Zhang & Yang, 2019) investigated the economic benefits of a coal-to-electricity project of power grid companies for residential heating. Du, Feng, Zhao, and Wang (2019) exploited a cooperative game theory to investigate how to maximize the environmental benefits by choosing an appropriate strategy with minimum cost in BTH regions. For more studies about the coal switching or control, please refer to Arora, Cai, and Jones (2016), Du, Feng, Wang, Zhao, and Liang (2018), and Chen and Chen (Chen & Chen, 2019).

For research on the effects on emission reduction, Zhao et al. (Zhao et al., 2019) examined the emission reduction contribution of the clean energy alternatives for heating, and found significant emission reduction. Liu et al. (Liu et al., 2019) adopted the GAINS model to probe the effect of mitigation strategies, including the coal switching measures in the residential sector of the BTH region, and found that the strategies reduced the primary $PM_{2.5}$ and sulfur dioxide (SO_2) emissions by 28% and 11%, respectively. Another interesting research project compared the emissions from different residential coal stoves in China's BTH region and found that high-quality coal replacement is also an important measure for reducing emissions (Tian et al., 2018).

In general, research about residential energy upgrade programs is quite rich. Nevertheless, due to the lack of data availability, there is a dearth of research concerns about residential scattered coal-replacement programs in China at the micro level. More quantitative analysis is needed to evaluate the effect of the program. Compared to existing research on China's coal-replacement programs, this paper ocuses more on micro-level impacts and household delivered energy.

To the best of our knowledge, Barrington-Leigh et al. (Barrington-Leigh et al., 2019) is the only research study similar to ours. They evaluated the impact of the program that subsidized electric heating devices and banned coal on household from multiple dimensions. However, our research is different in three aspects. Firstly, apart from *coal-to-electricity* policy, we also investigated China's *high-quality coal replacement* policy, which is an important alternative for areas having no capacity for the prevalence of electricity in large scale. Secondly, matching technique is exploited in our study to estimate the average treatment effects, which has a higher reliability for policy evaluation than direct comparison. More important, this study analyzed variation of household delivered energy, which is directly linked to the residents' service flow and welfare.

Methodology and data

Data description

We used data from the China Residential Energy Consumption Survey (CRECS) to quantify the effect of the coal-replacement program on fuel consumption.[2] The structured questionnaire collected information in 2016, including basic demographic characteristics, housing characteristics, the usage of various heating devices, the understanding and participation of the programs, and residents' attitudes towards the programs. The survey was conducted from June to August 2017 by Renmin University of China, and the sample area was rural and suburb areas of Beijing. The total number of valid questionnaires was 3949.

Following Wu, Zheng, Guo, Li, and Wei (2019a), we could estimate the energy consumed for heating by the usage information (including usage frequency, usage duration, the output power of the appliance, etc.) of the heating devices. In 2016, the total energy consumption for distributed heating was 713 kgce (kilogram of coal equivalent[3]) per household, while the energy consumption for the centralized district heating was 421 kgce per household for Beijing's rural area (including the suburb area). Fig. 1 shows the energy Sankey diagram based on the estimation. It clearly shows that coal dominates the fuel consumption for heating while fuelwood, natural gas and electricity follow. Boiler, kang,[4] stove and wall heater are the four most common heating devices in Beijing.

Three different interventions of the program were investigated: *coal-to-electricity, coal-to-gas* and *high-quality coal replacement*. Considering the sample size of our data, there were not enough observations for the analysis of the *coal-to-gas policy*. We therefore focused on the effect of the *coal-to-electricity* and *high-quality coal replacement* policies. To avoid the effect caused by multiple policies, we excluded the households that participated in multiple programs, as well as households equipped with the district heating, when conducting the empirical analysis.

Empirical methodology

The coal-replacement program has been implemented in several Beijing villages. Assignment to participate is by means of administrator selection. A straight and simple comparison of the mean fuel consumption of sample households who do and do not participate in the programs is likely to yield inaccurate estimates of the causal effect on the outcome. In this case, the ordinary least square (OLS) regression is not applicable to examine the treatment effect, since it does not consider the common support assumption, namely the similarity of the treatment groups and control groups. This assumption ensures that there is sufficient overlap of the treated and untreated groups.

There are various impact evaluation techniques to investigate the average treatment effect of interventions or shocks, including difference-in-difference (DID), regression discontinuity design (RDD), propensity score matching (PSM), and others. All of these methods have their own advantages and disadvantages. Since our questionnaire was designed only for ex-post outcome, the absence of the ex-ante outcome of two groups and the lack of a breakpoint made it difficult to use the DID and RDD methods. Therefore, we exploited the PSM method to explore the matching samples and examine the program impacts.

PSM is one technique of matching methods (Heckman, Ichimura, & Todd, 1998; (Rosenbaum & Rubin, 1983)), and it is based on a counterfactual inference model. It assumes that there should be an observed outcome and an unobserved outcome of each individual. As shown in Table 2, for individuals in the treatment group, the counterfactual outcome is the potential outcome ($E[Y_0|D = 1]$) if they are not treated; for an individual that is not treated, the counterfactual outcome is the condition ($E[Y_1|D = 0]$) if they are treated. A standard estimation of the average treatment effect on those treated should be the difference between the observable outcome and the counterfactual outcome of the treated group. Obviously, potential counterfactual outcomes cannot be observed.

In the absence of the counterfactual outcome of the treated group, we can just use the observable outcome of the controlled group to substitute the unobservable outcome of the treatment group. Then, the matching technique is needed to find the appropriate controlled group whose observable outcome can be regarded as the counterfactual outcome of the treated group. PSM is used to match the treatment group and control group by their propensity score; that is, the predicted probability that the household participate in the program from a probit or logit regression given a set of observable characteristics. Individuals in the controlled group with a lower propensity score than the lowest observed value in the treatment group and with a higher score than the maximum are discarded. The most important step for PSM is to select the covariates which attempts to control the differences to make the two groups comparable. After the construction of matching samples, the difference of the outcomes between the two groups is the average treatment effect on those treated by the policy. However, the average treatment effect is not enough to depict the treatment on individuals due to their different responses to the intervention. To further study the heterogeneity in the treatment effect, the matching-smoothing method (MS) is used, which can retain individual-level information to detect the heterogeneous treatment effect (Xie, Brand, & Jann, 2012).

The intervention of this study was the coal-replacement program, and the covariates we chose are the variables that not only affect participation but also have an influence on the outcome variables. The treatment variable is a binary variable that indicates whether the household received the policy intervention, and the outcome variables include household consumption in electricity, bituminous coal and anthracite. Apart from the direct effect on the consumption of electricity and coal, the policies are also likely to get residents to substitute coal with other cheaper and more available fuel, like firewood or crop residue. Thus, the variation of fuelwood consumption is also analyzed.

Matching covariates must be not the variables that are affected by the policy. Based on this principle, demographic covariates and dwelling covariates are selected. Following energy ladder theory ((Hanna & Oliva, 2015; Hosier & Dowd, 1987); van der Kroon, Brouwer, & van Beukering, 2013), the basic demographic covariates that affect fuel choice include household income, family size, and the householder's gender, age and education. We also consider the family structure — that is, whether there are older people or children in the family (Sardianou, 2008). For dwelling variables, the dwelling size, dwelling

[2] The Department of Energy Economics of Renmin University of China was in charge of the questionnaire design, interviewer training and data clearance; the National Survey Research Center at Renmin University of China was responsible for the sample selection and return visit; the Youth League Committee took responsibility for the recruitment and management of interviewers.

[3] Kilograms of coal equivalent is the standard unit used for energy in China. 1 kgce = 29.27 megajoules.

[4] Kang is a brick platform used for heating in northern China.

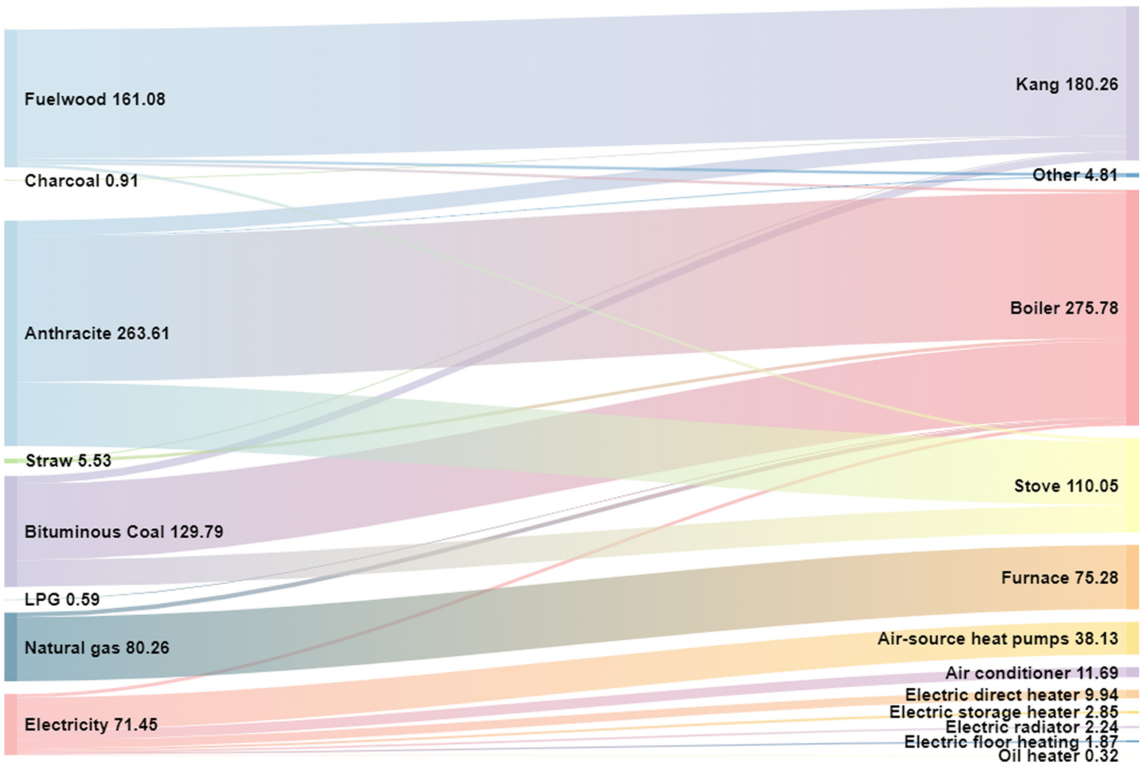

Fig. 1. Household energy Sankey diagram for space heating (unit: kgce).

age, dwelling property and whether the dwelling has been retrofit for insulation are selected (Engvall, Lampa, Levin, Wickman, & Öfverholm, 2014; Guerra Santin, Itard, & Visscher, 2009). Climate factors are important for residents' behavior in space heating, but our sample area is Beijing and the data are cross-sectional only for 2016, which means there is no significant temporal and spatial difference of the sample, so it is acceptable not to consider the atmospheric conditions. In addition, we also take the number of heating device into account. The diversity of the heating device influences the fuel choice, and the number of devices affect fuel consumption.

The participation of the *coal-to-electricity* and *high-quality coal replacement* interventions are shown in Table 3. We combine the bituminous briquettes, bituminous honeycomb coal and other chunk coal as the Bituminous Coal, and the anthracite briquettes and anthracite honeycomb coal as Anthracite. The ratio of households intervened by the *coal-to-electricity* policy and non-participating was 0.45, while the ratio was 0.69 for the *high-quality coal replacement* policy. There was significant (p-values $= 0.000$) disparity for the outcome variables, except for the firewood consumption ($p = 0.357$) in *high-quality coal replacement* policy. However, the simple comparison between treated groups and non-treated groups cannot be regarded to represent the program's treatment effect. Although similarity was observed between these two group for some demographic features, the t-statistics of household income and dwelling features indicate that there are significant differences between the treatment group and control group (e.g., the mean value of household income for participants in *coal-to-electricity* is higher than that of non-participants), which means the groups are not comparable. Then, the doubt of endogeneity issue arises, i.e., whether households with higher income consume more electricity spontaneously instead of as a result of policy intervention. Therefore, to lessen the endogeneity and obtain more reliable results, it is essential to use a matching method.

Table 2
The framework of counterfactual inference model.

Group	Y_1	Y_0
Treatment group ($D = 1$)	Observable $E[Y_1 \vert D = 1]$	Counterfactual $E[Y_0 \vert D = 1]$
Controlled group ($D = 0$)	Counterfactual $E[Y_1 \vert D = 0]$	Observable $E[Y_0 \vert D = 0]$

Results

Effects of the program on fuel consumption for space heating

To obtain a reliable result, we used the PSM method to make the treatment group and controlled group comparable. Many algorithms can be used for matching. Following Asensio and Delmas (Asensio & Delmas, 2017), we choose the algorithms with the lowest median bias. For the *coal-to-electricity* policy, in order to improve the balance of the covariates, except for the covariates mentioned in the methodology, we also added both the quadratic term and cubic term of household income and dwelling size. After trials, it indicated that the radius matching algorithm within a caliper of 0.05 leads to better covariate balance. For the *high-quality coal replacement* policy, the covariates selected were a little different from those of the *coal-to-electricity policy*, and the quadratic term and cubic term of dwelling size and the age of dwelling were excluded to meet the balance property in the matching process. The algorithm chosen was also the radius matching within a caliper of 0.05.

To show valid matching, it is essential to compare the observable characteristics for participants and non-participants. The difference of covariates between the treated group and untreated group before and after matching is shown in Fig. 2. Fig. 2a illustrates the improvement of balance, and the median bias of the covariates were 7.3% and 0.6% of the pre-matching and post-matching for the *coal-to-electricity* policy. The bias dropped from 6.4% to 0.6% for covariates of the *high-quality coal replacement* policy in Fig. 2b, which confirmed that the balancing was achieved. For all covariates, it is obvious that sample differences for

Table 3
Summary statistics of the participation in the coal-replacement program.

Variable	Non-participating households		Participating households		t-stat [c]
	Obs.	Mean	Obs.	Mean	
A. Coal-to-electricity policy					
Outcomes					
Electricity (kgce)	971	40.32	440	404.46	−20.6***
Bituminous Coal (kgce)	971	267.16	440	43.89	7.35***
Anthracite (kgce)	971	240.82	440	7.12	9.55***
Fuelwood (kgce)	971	273.87	440	79.03	5.05***
Demographic covariates					
Household income (yuan)	971	71,689.8	440	96,384.88	−2.4**
Family size (persons)	971	3.61	440	3.74	−1.3
Householder gender (0–1)	971	0.84	440	0.82	0.6
Householder education [a]	971	2.11	440	2.04	1.25
Householder age (years old)	971	57.38	440	57.5	−0.15
Family structure (Whether there are seniors or children, 0–1)	971	0.72	440	0.75	−1.1
Dwelling covariates					
Dwelling retrofit (Whether retrofitted with heat insulation, 0–1)	971	0.76	440	1.09	−4.9***
Dwelling size (m^2)	971	139.34	440	180.93	−5.6***
Dwelling property [b]	971	1.11	440	1.03	3.6***
Dwelling age (years)	971	20.75	440	20.26	0.6
Number of heating device	971	1.36	440	1.68	−5.4***
B. High-quality coal replacement policy					
Outcomes					
Electricity (kgce)	999	39.28	692	8.46	4.25***
Bituminous Coal (kgce)	999	266.53	692	142.76	4.7***
Anthracite (kgce)	999	238.67	692	893.07	−14.6***
Fuelwood (kgce)	999	273.82	692	242.02	0.9
Demographic covariates					
Household income (yuan)	999	70,453.88	692	70,193.54	0.05
Family size (persons)	999	3.61	692	3.5	1.3
Householder gender (0–1)	999	0.83	692	0.86	−1.25
Householder education	999	2.1	692	1.96	3.1***
Householder age (years old)	999	57.41	692	58.11	−1.15
Family structure (Whether there are seniors or children, 0–1)	999	0.72	692	0.72	0.05
Dwelling covariates					
Dwelling retrofit (Whether retrofitted with heat insulation, 0–1)	999	0.75	692	0.67	1.7*
Dwelling size (m^2)	999	139.01	692	179.36	−5.1***
Dwelling property [b]	999	1.13	692	1.05	3.95***
Number of heating device	999	1.36	692	1.57	−4.65***

Note: a. 0 = illiteracy; 1 = elementary school; 2 = middle school; 3 = high school; 4 = junior college; 5 = bachelor's degree; 6 = master's or doctorate degree; b. 1 = owner; 2 = lodge; 3 = rental; c. *** $p < .01$, ** $p < .05$, * $p < .1$.

matched cases are significantly lower than those in the raw data. Moreover, the balancing of each block was tested to ensure the balancing property in each block of this study. In addition, the kernel density was estimated for the propensity score before and after matching of two groups in Fig. 2c–f. The overlap of the post-matching curves of the treated group and untreated group visually reveals that the matching operation was successful.

After matching, the bias attributable to the observable variables was reduced and we could estimate the average treatment effect on the treated (ATT) by the difference in the mean outcomes of the matched samples. Table 4 presents the ATT estimates of two policies. The second column shows mean outcomes of the households intervened by the coal replacement policy, while the third column shows the mean outcomes of the matched untreated households. The difference between these two estimates is shown in the fourth column. The *coal-to-electricity* policy increased the electricity consumption of each household by 340.63 kgce for space heating, and the consumption of the treated group was more than seven times that of the untreated one. It also decreased the coal and biomass consumption by 362 kgce, to 307 kgce. Compared to the estimates with OLS regression (see Supplementary Table 1), it demonstrated that the absolute value of the effect of PSM is slightly larger than that of OLS. Households affected by the *high-quality coal replacement* policy greatly raised their anthracite consumption by nearly 580 kgce, while the consumption of other fuels decreased. For almost all cases, the effect of the *high-quality coal replacement* policy by using PSM was higher than that of OLS, except for the fuelwood consumption. The difference between the results from the PSM method and the OLS regression was not very significant, since there were only a small number of discarded unmatched cases. Before matching, the observations of treated and untreated groups were 440 (692) and 971 (999) for the *coal-to-electricity* policy (*higher-quality coal* policy), while the change affects only the sample size of the treatment group with its number of observations dropping to only 439 (689). The results in Table 4 support the hypotheses that the households which participated in the *coal-to-electricity* policy have higher electricity consumption and lower consumption of solid fuels, while the *higher-quality coal* policy leads households to consume more higher quality coal.

To avoid the hidden bias in the presence of unobserved heterogeneity that affects the assignment of the policy (DiPrete & Gangl, 2004), a Rosenbaum bound sensitivity analysis is utilized to assess the reliability of the estimates (Rosenbaum, 2014). Results from the tests are reported in Supplementary Table 2. The results remained reliable until unobserved variables caused the odds ratio of treatment assignment to the treated and untreated up to 3. We can therefore trust our matching results.

Heterogeneous treatment effect

It is possible that individuals respond differently to an intervention; for example, wealthier households may be more agreeable to using modern or cleaner fuels, while poorer households may be more willing to spend additional time collecting fuelwood or burning coal. The heterogeneous effect can be caused by any factors that affect residential fuel choice and fuel consumption. To illustrate the trend of the treatment effect on those treated varying with propensity score, Xie et al. (Xie et al., 2012) developed the matching-smoothing method which applies a nonparametric model to smooth the differences to yield a pattern of the heterogeneous treatment effect. Fig. 3a and b reflect the treatment effect heterogeneity on the fuel consumption of the *coal-to-electricity* policy and *high-quality coal replacement* policy, respectively. The *x*-axis shows the propensity score for the intervention, and the *y*-axis is the treatment effect on those treated. For the *coal-to-electricity* policy, the electricity consumption increases as the propensity score increases and the coal consumption decreases.

There is indeed a heterogeneity of effects for different scores. Households with the highest household income, largest family size, largest dwelling size and the greatest number of heating device who has the highest propensity score have the largest positive effect of the policy on the electricity consumption and the largest negative effect on coal consumption. In the case of the *high-quality coal replacement* policy, the household characteristics are not that obvious due to the existence of the extreme point of coal consumption for households with higher propensity scores.

Variation on delivered energy and air pollution

Delivered energy

The fuel consumption we mentioned in the sections above is the quantity that a household uses, but it does not reflect the actual heat service flow, since thermal efficiencies for different fuels and stove types vary greatly (Niu, Hu, Qian, & He, 2016; Zhuang, Li, Chen, & Guo, 2009). To examine the change of the delivered heat households obtained after the intervention, we used the coefficients of thermal efficiencies of fuel/stove provided by Zhang et al. (Zhang et al., 2000) and Wu, Zheng, You, and Wei (2019b) to calculate the delivered energy.

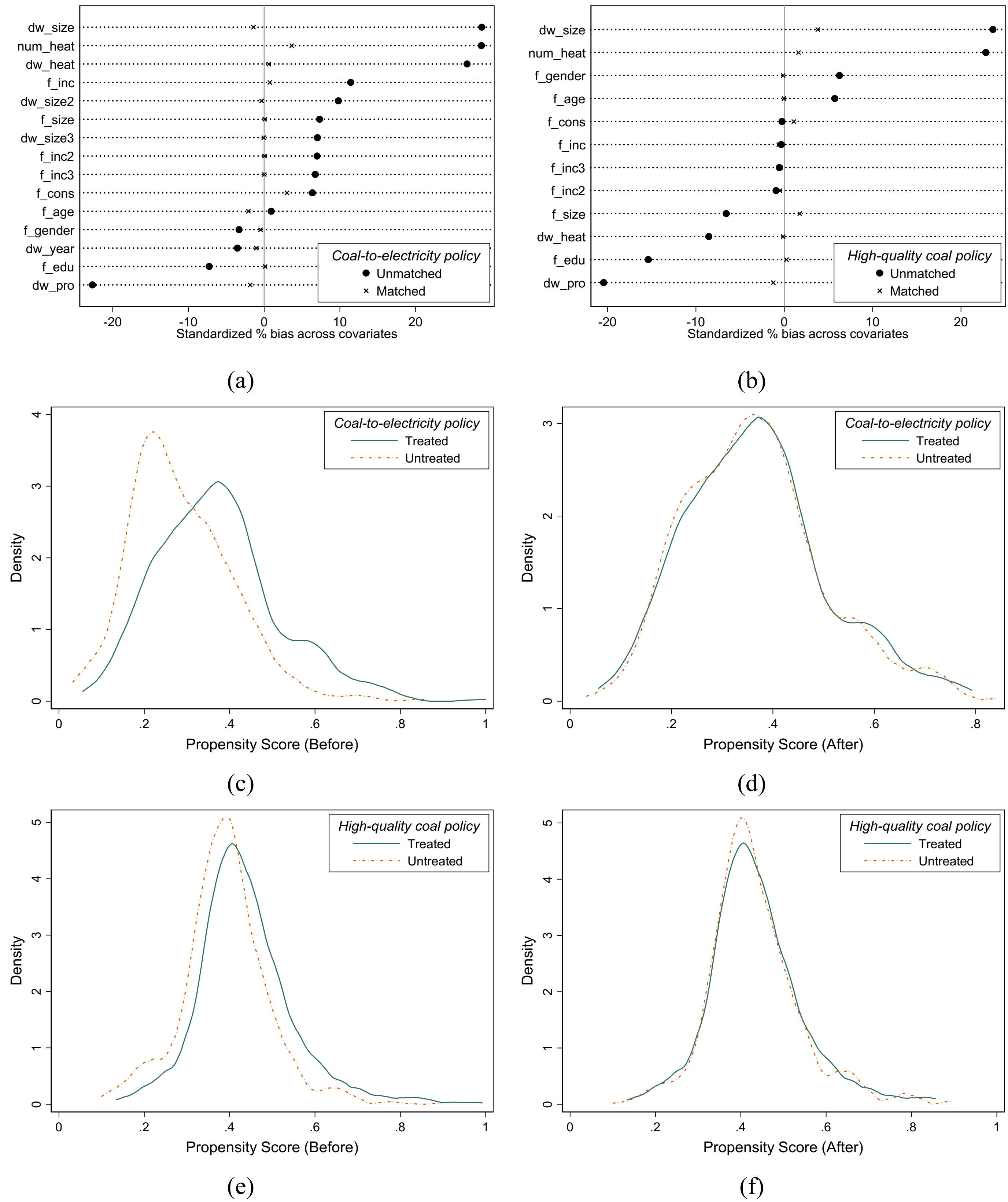

Fig. 2. Diagnostics of covariate balancing and kernel density of propensity score before and after matching.

Admittedly, our analysis did not cover all fuel types of household use for space heating but the four types of fuels we chose are the most common ones. Due to the lack of readily available information about product efficiency for coal stoves, our analysis also did not explicitly address possible differences in thermal efficiencies due to age, make and operating conditions.

Based on the results in Table 4, Table 5 presents the delivered heat actually released to the room. It demonstrates that the intervention of

Table 4
Average treatment effect of the coal-replacement program on fuel consumption for space heating.

Fuel	Treatment group(kgce)	Control group(kgce)	ATT (kgce)
A. Coal-to-electricity policy _ Radius method (0.05) ($N_t = 439$, $N_c = 971$)			
Electricity	395.40	54.77	340.63*** (22.11)
Bituminous coal	43.99	405.74	−361.75*** (27.35)
Anthracite	7.13	313.65	−306.51*** (21.01)
Fuelwood	79.21	323.18	−243.97*** (39.36)
B. High-quality coal replacement policy _ Radius method (0.05) ($N_t = 689$, $N_c = 999$)			
Electricity	8.50	49.73	−41.23*** (6.74)
Bituminous coal	143.38	361.02	−217.64*** (26.17)
Anthracite	847.61	268.81	578.80*** (42.84)
Fuelwood	243.08	311.00	−67.92 (36.13)

Note: *Nt* and *Nc* are the common support of the treatment group and control group; ATT is the average treatment effect on the treated; bootstrap standard errors are in parenthesis and *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

the *coal-to-electricity* policy deteriorates a household's delivered energy, while the *high-quality coal replacement* policy improves actual heat delivered. The delivered energy that households of the controlled group received was 393.98 kgce and 352.32 kgce for the *coal-to-electricity* and *high-quality coal replacement* policies, respectively. Due to the distinct thermal efficiencies of different fuels, fuel substitution affects a household's ultimate delivered energy. In contrast, the *coal-to-electricity* policy weakened the households' welfare in terms of delivered energy by 41.3 kgce, while the *high-quality coal replacement* policy enhanced delivered energy by 143.15 kgce — a significant change ($p = .000$).

Possible explanations for the decline of delivered energy due to the *coal-to-electricity* policy lie in the high fuel cost and difficulty in technology change from coal-based heaters to electric heaters. Even though the electric heater's high efficiency raises the delivered heat, it is offset by the reduction in the amount of fuel consumed due to electricity affordability. Electricity consumption increases as a result of the policy, but the incremental increase is not enough to maintain the previous heat levels. Respondents' response towards the policy also supports this conclusion — that is, the policy improves the convenience of heating and the indoor air quality but worsens overall delivered energy, as they are not willing to pay for additional electricity consumption due to the higher costs. Moreover, the financial subsidy is not adequate to cover the cost of electricity consumption for heating. A straggling power grid infrastructure also contributes to the decrease of delivered energy. The change from coal to electricity is not only a device issue, but also one of power load. The electricity infrastructure in rural China is generally poor, and cannot support a high-power load from many households using electric heaters.

Indoor air pollution

In addition to the delivered energy analysis used to examine the achievement of the warm winter goal, and we also estimate the variation of household indoor air pollution to assess the performance of the clean winter goal. Calculation of household air pollution is based on the physical amount of energy consumption multiplied by a constant emission factor of the specific fuel consumed. Emission factors for each fuel for each pollutant are derived from a number of studies ((Meng et al., 2019; Peng et al., 2019; Shen et al., 2015); Xie, Wu, Feng, Wei, & Zheng, 2019; (Xue et al., 2016); Yan, Ohara, & Akimoto, 2006; (Zhou et al., 2017)) and are listed in the Supplementary Table 3. Since we only focus on indoor emission, the electricity usage is regarded as non-polluting in terms of indoor air pollutants.

The results show that the treated group for the *coal-to-electricity policy* (*high-quality coal replacement policy*) emits $PM_{2.5}$ and PM_{10} emissions of 1.7 kg (14.0 kg) and 1.8 kg (12.2 kg), respectively, per household while the untreated group emits 15.3 kg (14.4 kg) and 15.7 kg (15.8 kg), respectively, per household. As for pollutants of SO_2, NO_X and CO, the untreated group emits 20.3 kg SO_2, 3.0 kg NOx and 175.4 kg CO more than the treated group per household for the electricity policy. For the high-quality coal replacement policy, the abatement effect is not as beneficial because the SO_2 and NO_X emissions for the treated household are found to be higher than the untreated household. The reduction in air pollution associated with decreased burning of bituminous coal and fuelwood in the high-quality coal replacement policy is actually offset by the more significant increase in anthracite coal consumption as seen in Table 5. In other words, although anthracite coal has lower emissions factors, its increase in the amount consumed outweighed the incremental decrease in emission factors when compared to bituminous coal and fuelwood. From the perspective of only indoor air pollution reduction, this highlights the limited effect of the policy of substituting low-quality bituminous coal with higher quality anthracite coal when compared to the policy of switching to electricity.

Our survey is only for limited samples, but we extend the results to the whole of Beijing. There were 582,500 households participating in *coal-to-electricity* by the end of 2016 (He, 2017) and 1,330,000 households related to the *high-quality coal* replacement (Bie, 2016). The

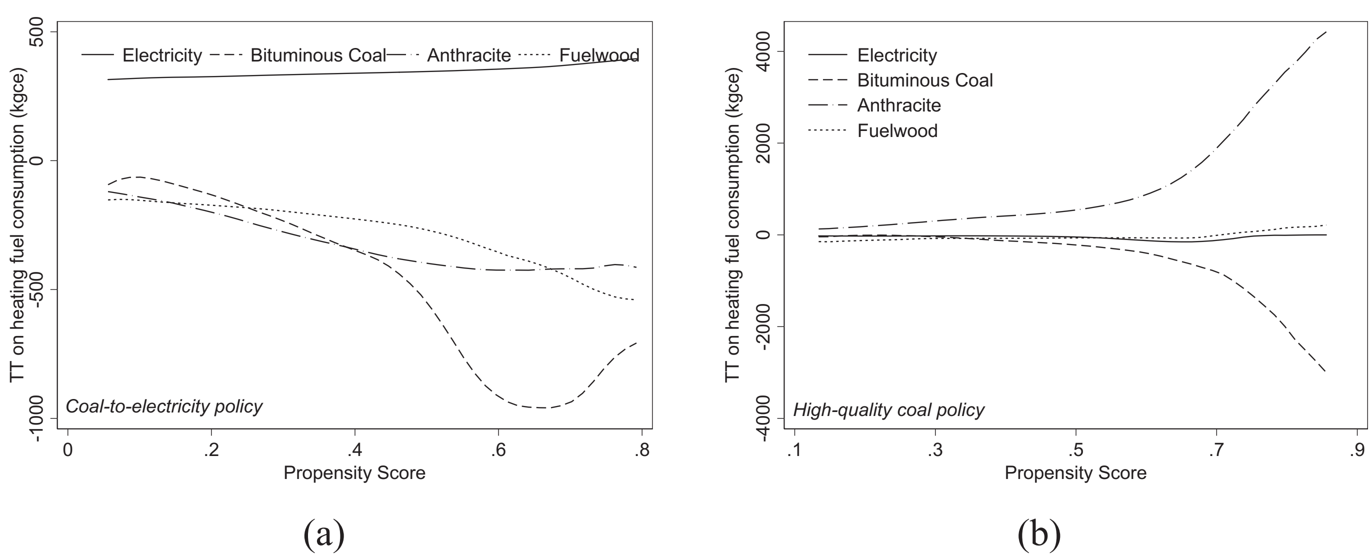

Fig. 3. Heterogeneous effect treatment on treated by the matching-smoothing method.

Table 5
Variation on the delivered energy.

Fuel	Thermal efficiency (%)	Treatment group(kgce)	Control group(kgce)	Difference (kgce)
A. Coal-to-electricity policy				
Electricity	80	316.32	43.82	272.51*** (17.69)
Bituminous coal	32.17	14.15	130.53	−116.38*** (8.80)
Anthracite	45.34	3.23	142.21	−138.97*** (9.52)
Fuelwood	23.96	18.98	77.43	−58.45*** (9.43)
Total		352.69	393.98	−41.30** (21.96)
B. High-quality coal replacement policy				
Electricity	80	6.80	39.78	−32.99*** (5.39)
Bituminous Coal	32.17	46.13	116.14	−70.01*** (8.42)
Anthracite	45.34	384.31	121.88	262.43*** (19.42)
Fuelwood	23.96	58.24	74.51	−16.27** (8.66)
Total		495.47	352.32	143.15*** (21.26)

Note: Standard errors are in parenthesis, and *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

counterfactual emissions of the treated households are the condition when they are not affected by the policies, thus we can regard the difference between the untreated group and treated group as the result of the policy. As shown in Fig. 4, we found that *coal-to-electricity* policy has a positive effect in improving residents' welfare as it reduces the indoor air pollution greatly. In 2016, the total reduction of $PM_{2.5}$ and PM_{10} emissions reached 7.9 kton (kiloton) and 8.0 kton in Beijing, respectively. Meanwhile, the policy reduces CO emissions by 100.2 kton. As previously discussed, the *high-quality coal* policy plays a limited role in battling air pollution since the SO_2 and NO_X had a slightly increase compared to the untreated group.

Discussion and conclusion

This study used real household data collected during the scattered coal replacement program to assess the effect of mandatory fuel substitution policies for space heating on household fuel consumption. By using the household survey conducted in Beijing area, and the PSM method, we estimated the average treatment effect of the governmental intervention on those treated. The sensitivity analysis of the Rosenbaum bounds on treatment effects at different levels confirms that our matching was sound and reliable.

The results indicate that the intervention had the desired effect on the fuel substitution, and there was significant increase in high-quality fuel and a reduction in inferior fuel. However, our results show that fuel substitution does not necessarily mean household delivered heat gain improved; that is, the fuel substitution goal was achieved but residents' actual heat was not as good as before. For the *coal-to-electricity* policy, households participating in the program achieved the goal of cleaner air with reduced indoor air pollution, but experienced a colder winter due to declines in delivered heat. While for the high-quality coal policy, there is a warmer winter with greater delivered heat from higher quality coal than before but there was no improvement to air pollution. This article also investigates the heterogeneity of the policy effect among different residents. The variations for solid fuels consumption were found to be more significant than those of electricity consumption, with an increase of the propensity scores regarding the electricity policy. But for the policy promoting substitution with higher-quality coal, the disparity mainly lies in a propensity score higher than 0.4 for the extreme consumption of bituminous coal and anthracite.

Even though this article focuses on a specific case for China, the results may help decision-makers cross different developing countries to re-think and better understand the possible impacts of policies focused on promoting fuel substitution to simultaneously improved thermal comfort and reduce indoor air pollution. By learning from China's case, we conclude the following two implications about fuel substitution for other developing countries that can be used to inform and improve policy design and implementation.

First, as the energy ladder suggests, advanced fuel substitution often occurs with a growth of household income and improvement of other socioeconomic factors. Under unchanging economic conditions, the design and implementation of mandatory fuel substitution policies needs to evaluate and prioritize affordability and availability criteria as these can affect the policies' actual impacts on substitution. Although financial subsidies for heating devices and heating fuel expenses can be provided, they may not be sufficient to achieve a sustainable fuel substitution as demonstrated in this study. Besides, energy is a systemic product that requires complementary goods (e.g., electric heaters that cannot be used when power is not available). The supporting energy infrastructure, particularly in the case of electricity, may be underdeveloped in the case of a low level of economic development, and this can significantly hinder the adoption of new, cleaner technologies. Effective fuel substitution policy implementation needs to be accompanied by related supporting policies, both on the demand side and supply side. Moreover, mandatory substitution narrows the household fuel choice to only one fuel. The arbitrary fuel substitution is contrary to the energy stack hypothesis as the household fuel substitution is not a linear process of one fuel replacing the other fuel completely. Fuel substitution is an incremental process rather than a leaping process.

Second, policy-makers need to pay more attention to the issues of energy poverty and energy inequality, as households from different

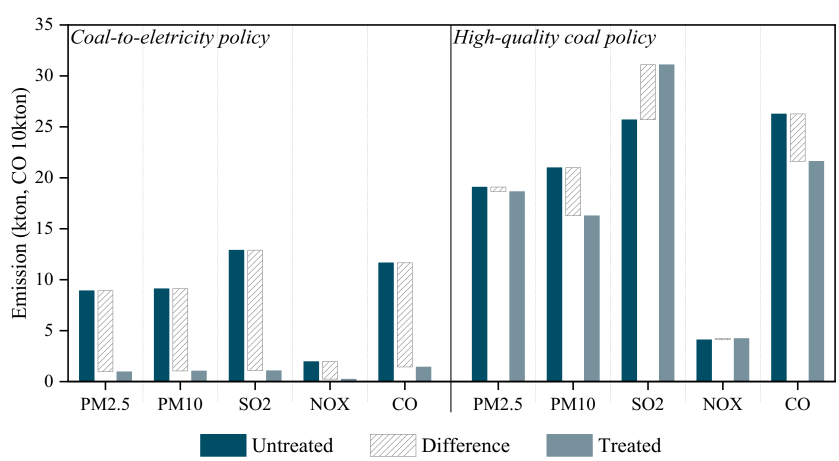

Fig. 4. Variation of indoor pollution for the policy in 2016 Beijing. Note: For *high-quality coal replacement* policy, the households in 2016 was replaced by the number in 2015 due to data availability.

backgrounds react inconsistently to policy interventions. It is possible that wealthy households tend to substitute coal by consuming more electricity without a subsidy than poor households with a subsidy, due to their different income elasticities. If the policy provides subsidies equally to all households, it encourages the rich to consume more electricity or high-quality coal, which exacerbates the energy inequality. Besides, there are still poor households that cannot afford the advanced fuel or devices even with subsidies. Targeted energy policies are needed to ensure the basic energy needs for the energy poor. Therefore, differential measures are needed to ameliorate the policy.

Current work is based on the cross-sectional survey data, which limits the temporal comparison of the effect. It is possible that households react differently to the policies in various years due to changes in weather, household income, health conditions, and other factors. Future work is expected to exploit the tracking household survey data to evaluate the continuity and sustainability of the policies, especially the data in three years, when the financial subsidy is removed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2020.02.002.

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